MESOSCALE SAMPLING OF GLOBAL RADIATION ANALYSIS OF DATA FROM WISCONSIN

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ABSTRACT

The time and space variability of global radiation have been studied using data collected from a mesoscale network of integrating pyranometers established in Wisconsin, for the period December 1966 through June 1967. The data have been normalized so that they are expressed as a percent of the clear day global radiation. The atmospheric transmission coefficient over the State changes from about 0.75 in winter to 0.60 in summer. For a typical month, the standard deviations of the State daily mean varied from a few percent up to 50 percent of the State mean. Mean day-to-day changes of approximately ± 18 percent-radiation were recorded. From use of records for any one site in the State, the global radiation elsewhere in the State can be estimated with an approximate standard error of ± 25 percent or less of the clear day radiation on a daily basis, ± 15 percent or less on a 5-day basis, and ± 10 percent or less on a monthly basis. Alternatively, if the network data from the sites surrounding the unknown point can be used for interpolation, the global radiation anywhere in the State can be estimated with an approximate standard error of ± 20 percent or less of the clear day radiation on a daily basis, ± 10 percent or less on a 5-day basis, and ± 6 percent or less on a monthly basis.

1. INTRODUCTION

The need for mesoscale measurements of global radiation has been emphasized in a recent report on bioclimatology which concludes that global radiation is one of the meteorological elements of sufficient biological significance for the Weather Bureau to include it in its nationwide observational program (Sargent [1]). In order to establish a mesoscale network, data are needed on the time and space variation in global radiation. These data can be used to ensure that the region is adequately sampled and that the mesoscale network of pyranometers is capable of providing the information required.

Although global radiation measurements have been made at Truax Airport, Madison, Wis., for many years, measurements have not been made elsewhere in the State. The Truax measurements provide information on the time variability of global radiation at one point, but it is not known how well this point represents the whole State. A mesoscale network of integrating pyranometers was established in the State during the fall of 1966. This paper discusses the time and space variability of global radiation determined from data collected from this network during the period from December 1966 through June 1967. The number and distribution of sampling sites necessary to make reliable estimates of the global radiation received over the State can be determined from this information.

2. PYRANOMETER NETWORK

The distribution of the integrating pyranometer sites in Wisconsin is shown in figure 1. The integrating pyranometers used in this study were made at the Department of Soil and Water Sciences, University of Wisconsin (Kerr et al. [2]). The network was built around the University of Wisconsin Experimental Farms, the ESSA Weather Bureau first-order airport stations, and the Bureau's cooperating observers. The State was covered as uniformly as practicable, although considerable difficulty was experienced in finding sites where the pyranometers could be mounted so that they would be exposed to the sun throughout the day at all times of the year. The pyranometers were read each day and the data were collected each month. Further details on the network are given by Kerr et al. [3].

3. NORMALIZATION OF THE DATA

There are several advantages to be gained for analysis by normalizing the data as a percentage of the clear day global radiation value at the given sampling site on the day of measurement. The normalization procedure allows the short-term variations about the mean to be studied as a function of time while eliminating the effect of the long-term time dependency of the mean itself. Normalization of the data also decreases systematic errors due to the pyranometer when comparisons are made between sites. Both the effects of latitude and of

FIGURE 1.—The pyranometer network in Wisconsin and St. Paul, Minn.

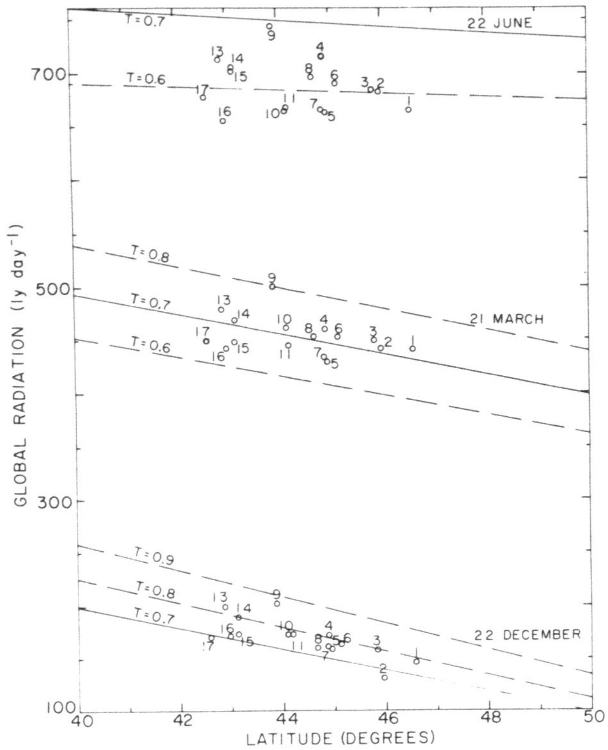

FIGURE 2.—Clear day global radiation for June 22, March 21, and December 22.

clear day variations in the atmospheric concentrations of aerosols and precipitable water are eliminated. Therefore, the variability in "percent-radiation" (the normalized data) is primarily due to the effects of the changing patterns of cloudiness, and secondarily to the changes in the atmospheric concentrations of aerosols and precipitable water which occur on cloudy days.

The clear day global radiation values at a given site were obtained by plotting the daily global radiation as a function of time and then drawing a freehand curve through the maximum points. It is assumed that there were sufficient clear days at all the sites to determine the true shape of the curve.

4. CLEAR DAY GLOBAL RADIATION

The clear day global radiation measurements were compared with values computed from data given by List [4], pp. 418, 421. The global radiation for clear skies was computed for December 22, March 21, and June 22 using the method described by List [4], p. 420, for latitudes 40° and 50°, and for transmission coefficients of 0.6, 0.7, 0.8, and 0.9. Supplementary calculations for latitudes 30° and 60° were made. These showed that between latitudes 40° and 50° the relationship between clear sky global radiation and latitude is approximately linear, for each transmission coefficient, T. Therefore, straight lines were drawn between these two points in figure 2. The estimates of the clear day global radiation at each site were interpolated from the maximum curves constructed from the measurements made at each site. The estimates for each site are identified in figure 2.

Figure 2 shows that the computed clear sky global radiation values are a function of latitude in December and March, but are practically independent of latitude in June over the range of latitude considered. This same dependence on latitude is shown by the general trend of the clear sky global radiation values measured at each site. The atmospheric transmission coefficient associated with the measured radiation values decreases from about 0.7 to 0.8 in December, to approximately 0.7 in March, and 0.6 in June.

The decrease in the atmospheric transmission coefficient from winter to summer is probably related to the increase in the precipitable water content of the atmosphere, and to the summer increase in ozone concentration (Miller [5]). The increase in the effective air mass from summer to winter and seasonal variations in the concentration of aerosols would affect the transmission coefficients to some extent.

It is difficult to explain the scatter of points in figure 2. The scatter could be due to local variations in the precipitable water content of the atmosphere, to poor estimates of the clear day global radiation value from the network measurements, or to local variations in the atmospheric concentration of pollutants on clear days. All these factors contribute towards low values of clear day global radiation. A systematic error in the pyranometer would either raise or lower the maximum radiation values. Consistently high clear day values were recorded at Site 9. The possibility of a pyranometer zero error was tested in May by exchanging the pyranometer at Site 9 with the one at Site 3—the same procedure used in eliminating thermometer zero error. The measurements at Site 9 remained high after this exchange, whereas at Site 3 were unchanged relative to the other sites. This suggests that the high readings at Site 9 are not likely to be caused by the pyranometer.

5. DAILY VARIABILITY

The space and time variability of percent-radiation in Wisconsin are demonstrated by the data for March in figure 3. Similar data were collected for the other months. The mean percent-radiation of the 16 sites, subsequently called the State mean, and its standard deviation, SD, are given for each day. The data were assumed to be normally distributed. During March the average change in the State mean between consecutive days was ± 18.3 percent-radiation, whereas the average change in the State mean between consecutive 5-day periods was ± 12.4 percent-radiation.

The SD provides one measure of the State-wide spatial variation of percent-radiation. On March 8 clear skies covered the State, on March 13 skies were comparatively clear in the north but clouds were present in the south, and on March 26 intense cloudiness covered the State. The respective percent-radiation means for these 3 days were 97.5, 48.7, and 18.0, and the corresponding SDs were ± 1.2, ± 23.0, and ± 6.9. On March 1 the whole State was under partial cloudy skies and the mean was 60.0 and the SD was ± 9.7 percent-radiation.

6. SPATIAL SAMPLING

The spatial variability of percent-radiation was examined in order to assess the adequacy with which the present network sampled the State. Comparisons were made between each pair of sites.

The correlation coefficient, r, regression coefficient, and the standard error of the estimate, S_{yx}, were computed for each pair of sites. The three groups of source data used in these computations were: i) the daily measurements, ii) the average daily values calculated for 5-day periods, and iii) the average daily values calculated for each month.

The quantity of data obtained from these calculations was reduced by selecting Sites 1, 6, 9, 11, and 15 for detailed study. These five Sites are representative of the northern, central, western, lakeshore, and southern regions. Each of these five regional Sites was chosen in turn as the independent variable, x, and used to estimate the percent-radiation at the other 15 sites.

The standard error of the estimates and the correlation coefficients calculated from the comparisons between sites based on the data for single days are presented in table 1. The results were similar for all months, and so the data have been presented for March alone. A gradient of mean daily percent-radiation existed across the State in March, from 73 in the north to 59 in the south.

Correlation coefficients, r, greater than 0.90 were obtained for seven of the 75 comparisons. For the comparison between Sites 14 and 15, $r=0.99$, and $S_{yx}=\pm 4.1$, but these two Sites are located in Madison about 5 mi. apart. In 10 cases, one or other of the regional sites could be used to estimate the daily percent-radiation at one of the 15 sites with $S_{yx}=\pm 13.8$ or less. Therefore, because

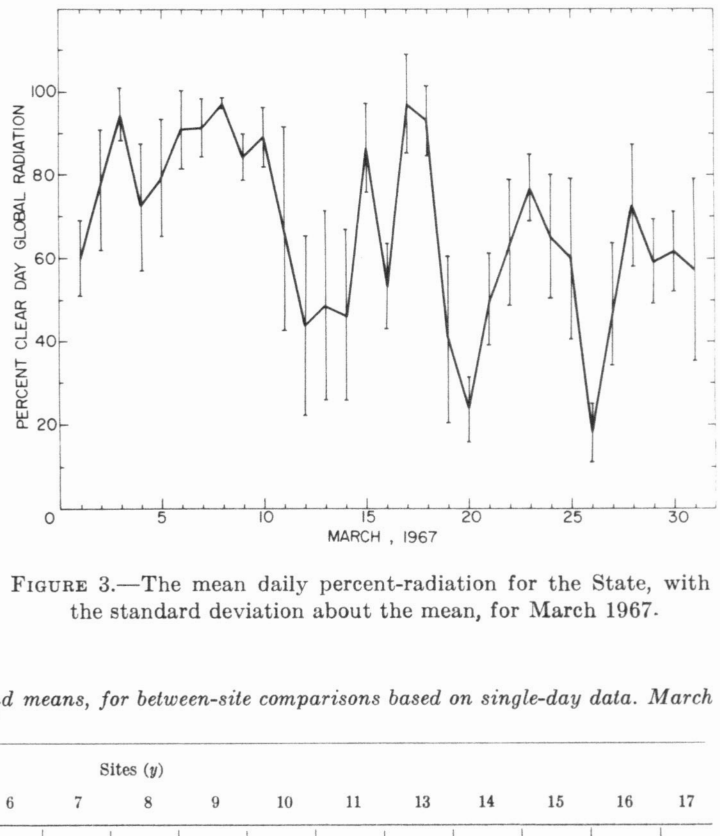

FIGURE 3.—The mean daily percent-radiation for the State, with the standard deviation about the mean, for March 1967.

TABLE 1.—*Standard errors of estimates S_{yx}, correlation coefficients r, and means, for between-site comparisons based on single-day data. March 1967*

Regional sites (x)		Sites (y) 1	2	3	4	5	6	7	8	9	10	11	13	14	15	16	17
1	S_{yx}	--------	15.0	16.3	20.2	20.9	15.4	16.7	19.9	22.6	20.0	20.8	23.4	22.3	22.6	23.8	24.4
	r	--------	0.79	0.79	0.61	0.63	0.77	0.64	0.61	0.61	0.44	0.53	0.38	0.54	0.50	0.37	0.44
6	S_{yx}	15.6	10.2	15.0	18.6	12.8	--------	8.7	10.7	14.2	15.9	18.2	19.4	18.6	18.8	21.2	21.5
	r	0.77	0.91	0.83	0.68	0.88	--------	0.92	0.90	0.87	0.70	0.67	0.64	0.71	0.69	0.56	0.61
9	S_{yx}	19.3	17.1	15.4	15.0	12.5	12.0	14.3	10.3	--------	14.4	21.1	15.9	16.1	16.6	20.5	17.4
	r	0.61	0.72	0.82	0.81	0.88	0.87	0.76	0.91	--------	0.76	0.50	0.78	0.80	0.77	0.60	0.77
11	S_{yx}	20.7	19.2	22.8	23.5	22.8	17.9	13.4	21.8	24.5	20.7	--------	24.2	21.2	20.9	19.2	23.5
	r	0.53	0.63	0.52	0.38	0.53	0.67	0.79	0.49	0.50	0.37	--------	0.29	0.60	0.66	0.66	0.50
15	S_{yx}	21.0	21.7	20.4	20.1	18.7	17.2	15.4	18.6	18.1	14.8	19.6	13.0	4.1	--------	10.8	8.6
	r	0.50	0.48	0.64	0.61	0.72	0.69	0.70	0.67	0.77	0.75	0.60	0.86	0.99	--------	0.91	0.95
	Mean	72.9	73.1	68.2	68.7	71.1	71.4	73.8	69.2	64.5	70.1	63.4	61.6	61.0	61.7	58.5	60.5

TABLE 2.—Standard errors of estimates S_{yx}, correlation coefficients r, and means, for between-site comparisons based on 5-day data. *December 1966 to June 1967*

Regional site (x)		Sites (y) 1	2	3	4	5	6	7	8	9	10	11	13	14	15	16	17
1	S_{yx}	--------	8.4	5.8	7.4	8.2	8.4	10.1	8.5	11.6	10.2	13.0	11.9	11.8	12.8	13.2	13.8
	r	--------	0.82	0.90	0.81	0.79	0.82	0.69	0.76	0.66	0.71	0.53	0.52	0.61	0.56	0.49	0.50
6	S_{yx}	7.3	7.4	8.6	7.9	7.7	--------	6.4	5.1	9.8	6.7	10.1	9.8	10.3	10.6	11.1	11.6
	r	0.82	0.86	0.77	0.78	0.82	--------	0.89	0.92	0.77	0.88	0.75	0.71	0.72	0.73	0.69	0.68
9	S_{yx}	9.3	11.5	8.9	7.4	6.5	9.3	9.6	7.3	--------	6.4	9.4	8.4	6.8	8.3	8.1	9.4
	r	0.66	0.63	0.75	0.80	0.88	0.77	0.74	0.83	--------	0.90	0.80	0.81	0.89	0.85	0.85	0.81
11	S_{yx}	10.2	10.2	10.7	10.2	10.3	9.2	7.1	6.9	9.3	8.8	--------	11.6	9.8	10.9	8.2	12.0
	r	0.53	0.69	0.60	0.58	0.64	0.75	0.85	0.84	0.80	0.79	--------	0.56	0.75	0.71	0.84	0.66
15	S_{yx}	10.8	12.9	10.6	8.9	8.7	10.1	10.0	8.9	7.8	6.0	10.4	5.6	2.5	--------	5.7	4.3
	r	0.56	0.51	0.62	0.70	0.75	0.73	0.71	0.75	0.85	0.91	0.71	0.92	0.99	--------	0.92	0.96
	Mean	65	64	65	66	65	66	67	64	64	68	62	65	63	65	64	67

TABLE 3.—*Standard errors of estimates S_{yx}, correlation coefficients r, and means, for between-site comparisons based on monthly data. December 1966 to June 1967*

Regional sites (x)		Sites (y) 1	2	3	4	5	6	7	8	9	10	11	13	14	15	16	17
1	S_{yx}	--------	3.5	3.5	6.1	3.8	2.8	3.5	3.3	6.3	2.6	5.2	7.4	8.2	8.5	7.2	8.7
	r	--------	0.87	0.73	0.66	0.85	0.92	0.88	0.89	0.37	0.91	0.31	0.31	0.49	0.48	0.09	0.22
6	S_{yx}	2.5	4.9	2.7	5.4	3.5	--------	4.0	1.6	5.6	1.4	5.0	6.4	7.1	7.1	6.8	7.7
	r	0.92	0.73	0.85	0.74	0.87	--------	0.85	0.98	0.55	0.98	0.40	0.58	0.66	0.69	0.35	0.50
9	S_{yx}	6.1	6.1	2.4	4.9	6.1	6.1	5.7	6.0	--------	2.1	2.1	4.3	5.4	6.1	3.4	6.4
	r	0.37	0.51	0.88	0.79	0.54	0.55	0.66	0.58	--------	0.96	0.92	0.83	0.82	0.78	0.88	0.70
11	S_{yx}	6.2	5.9	3.5	6.4	6.7	6.7	5.8	6.5	2.6	5.7	--------	6.3	7.4	8.1	5.0	8.1
	r	0.31	0.56	0.72	0.61	0.37	0.40	0.64	0.48	0.92	0.47	--------	0.58	0.62	0.55	0.72	0.41
15	S_{yx}	5.7	6.2	2.7	3.1	4.5	5.3	5.6	5.8	4.2	4.5	4.6	2.5	1.5	--------	3.6	3.0
	r	0.48	0.50	0.85	0.92	0.78	0.69	0.69	0.62	0.78	0.71	0.55	0.95	0.99	--------	0.87	0.94
	Mean	65	64	65	66	65	66	67	64	64	68	62	65	63	65	64	67

day to day variations in percent-radiation are so large, daily estimates of global radiation at any given location in the State are best obtained by actual measurements, particularly if the location is more than a few miles from a pyranometer. The average distance between the pyranometer sites in the State is 80 mi.

The analysis was repeated using the 5-day data accumulated over the December–June period, and the results are presented in table 2. Correlation coefficients greater than 0.90 were obtained for eight of the between-site comparisons. The daily percent-radiation was estimated within ± 13.8 percent and in nine cases to within ± 6.4 percent of the clear day radiation. The prediction of 5-day totals of global radiation anywhere in the State with standard errors of ± 6.4 percent-radiation or less, can only be achieved if data from a neighboring site are used and if more sampling sites are added to the present network. Additional sites are required in the north-central region and west of the Lake Michigan shoreline. Considerable error is incurred if the measurements made at the ESSA Weather Bureau first-order station at Truax Airport are used to estimate values elsewhere in the State.

The results from the analysis using monthly means of daily values for the December–June period are presented in table 3. Correlation coefficients greater than 0.90 were obtained for 12 of the comparisons. Values of S_{yx} were less than ± 8.7 percent of the clear day radiation and in 14 cases were less than ± 3 percent. The records at Truax could be used to estimate values elsewhere in the State with a maximum standard error of ± 6.2 percent of the clear day radiation on a monthly basis.

The variability of the data is reduced by increasing the number of days over which the data are averaged. The change in S_{yx} is roughly proportional to $n^{-1/2}$, where n is the number of days in the period, but there is not a corresponding increase in the correlation between the sites.

TABLE 4.—*The number of days with 0–30, 30–70, 70–100 percent-radiation,[1] at the regional sites. Data for December 1966, March 1967, June 1967, and December 1966 through June 1967*

	Dec.			Mar.			June			Dec.-June			
Site	0-30	30-70	70-100	0-30	30-70	70-100	0-30	30-70	70-100	0-30	30-70	70-100	0-100
1	5	14	12	2	7	22	6	13	11	24	81	107	212
										11	38	51	100
6	6	7	18	2	14	15	9	10	11	30	69	113	213
										14	33	53	100
9	10	4	17	5	13	13	1	13	14	32	76	101	209
										15	36	49	100
11	9	7	15	2	15	14	4	13	12	36	75	98	209
										17	36	47	100
15	10	4	9	6	13	12	3	10	17	32	68	104	204
										16	33	51	100

[1] Percent of clear day radiation which would occur on the date of measurement.

Data from the network can be used to estimate global radiation at any location in the State by interpolation from the records of the surrounding pyranometer sites. Some information on the error involved can be gotten by examining tables 1–3 and comparing the regional sites with their neighboring sites. From this examination it appears that the estimation of global radiation anywhere in the State can be made with an approximate standard error of ±20 percent or less of the clear day radiation on a daily basis, ±10 percent or less on a 5-day basis, and ±6 percent or less on a monthly basis.

7. FREQUENCY DISTRIBUTION

The measurements for each of the regional sites have been classified according to the percent-radiation received each day. The frequency distributions are given in table 4. Approximately half the days during the December–June period recorded more than 70 percent-radiation whereas only 11–17 percent of the days received less than 30 percent-radiation. Two Rivers experienced the greatest number of low radiation days. The distributions were similar at all sites over the 7-mo. period, but on a monthly basis there were significant differences between the distributions recorded at each site. In December high radiation days were fewer at Truax (Site 15) than at Antigo (Site 6), but in June the position was reversed. Some of the weather systems which were responsible for the frequency of both high and low radiation days have been discussed by Kerr and Rosendal [6].

8. CONCLUSIONS

The clear day global radiation values obtained at the 16 sites are consistent with the values calculated using List's [4] data. The clear day values show the variation of global radiation with latidude, especially in winter. The data also show that the atmospheric transmission coefficient decreases in the summer throughout Wisconsin.

Time and space variations of global radiation can be large. In March, the SDs varied from a few percent up to 50 percent of the mean, depending on the cloud systems prevailing over the State. Mean day to day changes of approximately ±18 percent-radiation were recorded.

The number and distribution of sites required in a mesoscale network depend on the type and accuracy of information required. The number of days over which the data are to be averaged, whether this be one, five, or more, as well as the spatial variability of global radiation, determines the size of the area represented by one pyranometer. Using records from any one site in the State, the global radiation elsewhere in the State can be estimated with an approximate standard error of ±25 percent or less of the clear day radiation on a daily basis, ±15 percent or less on a 5-day basis, and ±10 percent or less on a monthly basis. Alternatively, if the network data from the sites surrounding the unknown point can be used for interpolation, the estimation of global radiation anywhere in the State can be made with an approximate standard error of ±20 percent or less of the clear day radiation on a daily basis, ±10 percent or less on a 5-day basis, and ±6 percent or less on a monthly basis.

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